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# CARTESIAN AND ADAPTIVE METHODS FOR COMPLEX GEOMETRIES

## AFOSR

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### Objectives

The goals of this research are to develop high resolution adaptive tools to automate the CFD process from CAD through post-processing. This includes automated mesh generation for inviscid simulations, efficient flow solvers for heterogeneous computing environments, and adaptive remeshing of geometry in relative motion. Most of this research is in collaboration with Michael Aftosmis at NASA Ames Research Center.

### Status of Effort

Two major efforts are in progress this year. The first is on-going development of solution adaptive mesh refinement for use with Cartesian embedded boundary meshes. The second effort is developing numerical methods for time dependent flows, including moving geometries. This includes ongoing work in collaboration with Scott Murman at NASA Ames, using a dual time stepping approach that builds on our previous research developing a steady state flow solver. In a new collaboration with Christiane Helzel, a postdoc at the Courant Institute, we are trying to more fully understand the accuracy and stability issues of irregular grids, and develop explicit finite volume schemes that use time steps based on the full cell volumes.

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## Solution Adaptive Refinement

Until this year, our multilevel Cartesian meshes based the refinement on estimates of the curvature of the geometry. The refinement was performed once, in the mesh generation phase preceding a simulation. It is clear that for accurate high resolution solutions we need adaptivity based on the solution as well. The steps involved in solution adaptive mesh refinement are by now well understood, at least schematically. At specified timesteps throughout the computation, the time stepping stops, and you (i) decide where the solution needs refinement; (ii) refine the mesh (using mesh smoothing and buffering rules as appropriate); (iii) interpolate the old solution to the new mesh; and (iv) continue with the flow computation. In practise, all but step (i) are straightforward, although if the other steps are done in a parallel environment, new difficulties are presented.

Steps (ii-iv) have been completed for our Cartesian meshes, with the added benefit that in rethinking some of the mesh generation algorithms, the whole process is now roughly twice as fast. The difficulty still lies in step (i) - the criteria on which to base the refinement. In previous work we used Richardson estimates (or  $\tau$  extrapolation) to estimate the local truncation error. However the grid irregularities on unstructured embedded boundary Cartesian meshes mean that the truncation error isn't a reliable indicator of the error in over half the mesh. For example, the local error at the cut cells next to the geometry and at mesh interfaces is an order of magnitude larger than at regular cells. Coupled with the fact that the estimates are measured on the second finest level, only 30% of the mesh might end up with an estimate.

Thus recent work has focused on determining other criteria with appropriate scaling behavior to use to trigger refinement. First we mimic the behavior of the local truncation error (which for a second order scheme is reduced by a factor of 4 after refinement by 2) by scaling a first undivided difference quantity (appropriately normalized) by  $h$ . Second, we try to equidistribute this quantity over the domain while guarding against overresolving some flow features and ignoring others. Due to the extreme variation in the flow, most cells will tend to have a small error but a few are extremely large (for example at shocks). The mean will tend to be small, and the standard deviation large. Thus refinement based on the mean and standard deviation will overresolve shocks without ever addressing smooth regions of the flow. Instead of trying to filter out shocks and other strong features, we instead compress the scales by taking  $\log_2$  of the refinement parameter before computing its statistics. Note that in a histogram of the log of the refinement parameter, if a cell is refined by 2, the new cells will be translated approximately two units to the left in a new histogram. Thus, the threshold for refinement should be chosen to be two units to the right of the mean (or to the right of whatever the desired final equidistributed level is). This thresholding algorithm is described in [4] and includes several examples.

## H-box Methods for Irregular Grids

In collaboration with Christiane Helzel at Courant we are examining methods for time dependent flows based on explicit difference schemes. The goal is to construct schemes that are stable based on the time step  $\Delta t$  needed for the regular grid cells even though the cut cells can be many orders of magnitude smaller than a regular grid cell. There are several Cartesian grid methods in the literature that are stable. Achieving an accurate approximate at the boundary is the much more challenging task. So far no method has been found that leads to a second order accurate approximation.

We are currently looking at the so-called  $h$ -box methods, where  $h$  represents the length of a regular grid cell. In previous work with LeVeque an rotated difference scheme was developed that was accurate and stable, but the scheme was too complicated to extend to three dimensions. In order to develop more accurate methods we have recently been studying  $h$ -box methods in the simpler one-dimensional context. We have developed a high resolution method which we can prove leads to a second order accurate approximation of smooth solutions on non-uniform grids, without any restrictions on the grid. We can also prove stability of this second order method on a model problem for the case of an arbitrarily small cell. Numerical studies show that the same accuracy can be obtained for the approximation of nonlinear systems of conservation laws, in particular the Euler equations. This work is described in [1]. We are now trying to extend this work to two dimensions while maintaining stability using a simpler mechanism than the rotated scheme used.

## Accomplishments

This year the first phase of development our adaptive mesh refinement algorithm, described more fully above, was completed. It was used in the figure shown below. In this computation there were four adaptation cycles, resulting in a final mesh of 6 million cells. Undivided differences in the magnitude of the velocity were used to trigger the refinement. The region of refinement was constrained to the near body region so that shocks a distance away were not excessively refined. The refinement was done completely automatically, using the thresholding algorithm described above. This missile has tail fins that are free to rotate due to aerodynamic forces, although in this computation they are locked in place.

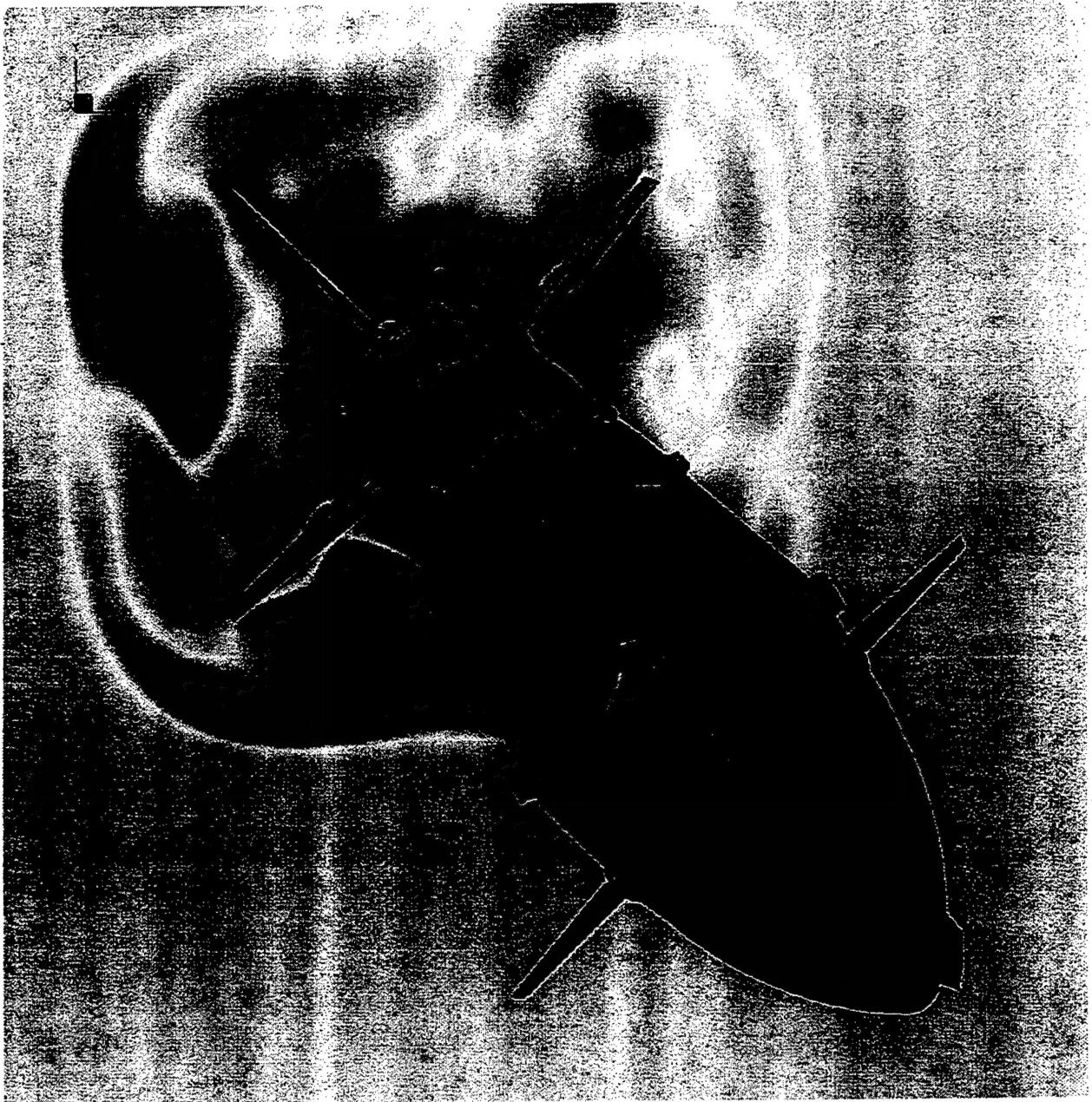


Figure 1: Pressure contours on a generic surface launched missile computed with Cart3D using adaptive mesh refinement.

## **Personnel**

This year the grant is supporting one faculty member (Marsha Berger) for two summer months, and a graduate student for the academic year and two summer months. A second graduate student was supported for the academic year only.

## **Publications**

- [1] "H-box methods for the Approximation of Hyperbolic Conservation Laws on Irregular Grids", with Christiane Helzel and Randy LeVeque. CMCL Report 92-001, April, 2002. Submitted to SINUM.
- [2] "Grid aligned h-box methods for conservation laws in complex geometries", with Christiane Helzel. Submitted to Proc. 3rd Intl. Symposium on Finite Volumes for Complex Applications, Porquerolles, France, July, 2002.
- [3] "Progress in the Simulation of Steady and Time Dependent Flows with 3D Parallel Unstructured Cartesian Methods", with M. Aftosmis and S. Murman. Submitted to the Second Intl. Conf. on Computational Fluid Dynamics, Sydney, Australia, July, 2002.
- [4] "Multilevel Error Estimation and Mesh Adaptation for Cartesian Meshes with Embedded Boundaries", with M. Aftosmis. AIAA Paper 2002-0863, Reno, NV., Jan. 2002. Submitted to AIAA Journal.

## **Interactions/Transitions**

### **Presentations**

Invited talk - Fred Howes Memorial Conference, Dept. of Energy.

### **Consultative and Advisory Functions**

I spend two months a year at NASA Ames, working closely with my collaborator Michael Aftosmis on the projects described here. I have collaborations with Phil Colella and John Bell at Lawrence Berkeley Laboratory, and with David Brown and Bill Henshaw at Lawrence Livermore Laboratory, on adaptive methods, grid generation, and Cartesian methods for embedded boundaries. Applications include accelerator modeling, plasma simulations, combustion, and other applications of interest to the Department of Energy.

## **Transitions**

Our research is disseminated through our software package Cart3D. It has been distributed for beta testing to over 130 sites, including industry, government labs, and universities. Most recently a copy of Cart3D was requested by Leth and Associates for modeling the stresses on the tail due to turbulence from a leading airplane (the American Airlines Dominican Republic flight that crashed last November). Their work is funded by the FAA and the NTSB.

One of the largest users continues to be the Defense Intelligence Agency (DIA), Missile & Space Intelligence Center. At DIA/MSIC, Dr. Alan Nicholson and co-workers are responsible for numerically simulating the aerodynamics of foreign missiles. DIA typically runs 4000 cases/day with Cart3D, and the software forms the heart of the agencies ability to predict the behavior of foreign surface-to-air missiles. The point of contact is Alan Nicholson (256-313-7418).

The DIA setup is now being replicated by the US Air Force NAIC facility at Wright Patterson AFB. NAIC focuses exclusively on foreign air-to-air missiles. NAIC has just begun this effort, and is still in the prototyping phase. So far they have used Cart3D to obtain solutions on 6 threat missiles, and are developing post-processing capability to generate the aerodynamics table neededs for their trajectory simulation programs. Dr. Jim Simon (937-257-2653) is the point of contact.

Many other projects use Cart3D, including design work at Eclipse Aviation, Boeing, and other NASA centers (in addition to the projects at the DOE Laboratories mentioned above). Mike Aftosmis (650-604-4499) is the point of contact for most of these.

## **New Discoveries, Inventions or Patent Disclosures**

The NASA Ames Commercial Technology Office has licensed the Cart3D software to ICEM CFD in several application areas.

## **Honors and Awards**

Cart3D is the NASA Ames nominee for NASA's Software of the Year award for 2002.